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ELECTRON AND PHOTON BEAMS AT NAL

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July 12, 1968

Introduction

C. A. Heusch[1] has given an extensive survey of methods to produce electron and photon beams at a 200-GeV accelerator. This note is a commentary on that work and extends it somewhat.

Basic Beam

What seems the most promising method to make pure electron and photon beams is illustrated in Fig. 1. The extracted proton beam interacts in a light element (Be) target, followed by a sweeping magnet to remove charged-particle background. Photons from π^0 decay convert to e^+e^- pairs in a radiator, R1. The thickness of this radiator will most likely be about 0.3 radiation lengths. There follows a standard beam-transport system focused on the EPB target, from which the e^+e^- pairs appear to originate. At the end of the beam, the electrons may be used directly (in which case a gas threshold counter is probably necessary) or to produce a photon beam in a second radiator. The photon beam may be "tagged" at this point.

Advantages of this Method

The electrons produced in R1 make such small angles with the direction of the photons producing them that they appear to come directly from the EPB target. There is only a small amount of broadening of this virtual source, due to multiple coulomb scattering in R1.

This has the consequence that converting the π^o decay photons outside the EPB target rather than in it does not increase the phase volume occupied by the electrons. Therefore, using a high Z target in the first place and taking electrons from it will not result in any flux increase other than that due to a marginal increase in the number of protons interacting. And, of course, the pion background in a charged beam looking at the EPB target would be very severe.

In a 0.3 radiation-length radiator (high Z), about one to two percent of the neutron (K^o, Λ^o, etc.) background will interact to produce secondary charged pions. These pions are produced at relatively large angles to the direction of the incident particle, and will appear to come from a diffuse region around the target. Coulomb scattering in 0.15 radiation lengths imparts an RMS transverse momentum of 8 MeV/c to the electrons. The mean transverse momentum of the pions produced in R1 will be of the order of 300 to 400 MeV/c. If R1 is placed so that the apparent source diameter due to multiple coulomb scattering is slightly greater than the real target diameter, the diffuse source of the pions will have a 40 to 50 times bigger diameter than the apparent source of electrons. The pion contamination, small to begin with, can therefore be reduced by a factor of more than a thousand by collimation at a double, dispersion-free, focus of the beam.

Finally, we note that the design of the beam-transport system for the electrons is in all ways identical with normal charged-particle beam design. In fact, any hadron beam can easily be converted to an electron or photon beam by the addition of a sweeping magnet and radiator upstream of the first beam element. The sweep magnet should be oriented to bend vertically. If the dispersion-free second focus of such a beam is to be used to collimate out the pion halo, a final imaging stage will be needed. One point of difference is that the vacuum requirements will be more stringent; breaking the vacuum near a focus of the beam will not, in general, be possible.

Electron (Positron) Fluxes, Radiator Thickness

As pointed out by Heusch,[1] the electron flux from a thin radiator is related to the π^0 flux by the expression

$$N(E_\pm)\,dE_\pm = t\,dE_\pm \int_{k=E_\pm}^{E_{max}} \frac{1}{k}\left[2\int_{E_{\pi^0}=k}^{E_{max}} \frac{N_{\pi^0} E_{\pi^0}}{E_{\pi^0}}\, dE_{\pi^0}\right] dk \qquad (1)$$

t is the (thin) radiator thickness in radiation lengths, $N(E_\pm)$ is the electron flux per steradian, GeV, and $N(E_{\pi^0})$ is the π^0 flux per steradian, GeV.

The π^0 decay opening angle is neglected. Since the transverse momentum to the photon in the decay is less than 70 MeV/c, compared with the ~ 350 MeV/c in the production process, the photon angular distribution will be very similar to the π^0 angular distribution at high energies.

In order to get an idea of what is going on, the Hagedorn and Ranft 0^o π^+ flux[2] has been approximated by the expression

$$N(\pi^+) = A(E_o - E) \text{ per GeV, per steradian}. \tag{2}$$

In the region from 70 GeV to 140 GeV this is a very good approximation, with A = 12.6 per steradian, per GeV^2 and E_o = 150 GeV. This will give an overestimate of ~ × 2 for the π^o flux.

Performing the integrations of Eq. (1) with E_o as an upper limit, we get

$$\frac{N(E_\pm)}{2AE_o t} = 1 - \frac{E_\pm}{E_o} - \ell n \frac{E_o}{E_\pm}\left[1 - \frac{1}{2}\ell n \frac{E_o}{E_\pm}\right]. \tag{3}$$

With the values given above for the constants, this leads to a spectrum which may be approximated, crudely,[3] by a power law

$$\frac{N(E_\pm)}{t} \sim B(E_\pm)^{-n} , \tag{4}$$

where n ≈ 10.

For a thick radiator (t ≳ 0.1) we must write

$$N(E_1)dE_1 = \int_{t=0}^{T}\left[\int_{E_\pm=E_1}^{E_{max}} \frac{\left(\frac{N(E_\pm)}{t}\right)}{E_\pm} \frac{\left(\ell n\left(\frac{E_\pm}{E_1}\right)\right)^{\left[\frac{4}{3}(T-t)-1\right]}}{} dE_\pm\right]dt . \tag{5}$$

This just incorporates the straggling formula of Bethe and Heitler as quoted by Tsai and Whitis.[4] It is depleted at the high energy end, compared to Eq. (1).

To get an idea of what a thick radiator does, we will consider the fate of the electrons produced in dt as T - t = 0.75. Eq. (5) then becomes

$$N(E_1)\,dE_1 = dt \int_{E_1}^{E_{max}} \frac{\left(\frac{N(E_\pm)}{t}\right)}{E^\pm} \, dE_\pm \,, \tag{6}$$

with $N(E_\pm)$ given by Eq. (1). If we insert into this the approximate power law expression of Eq. (4), we get

$$N(E_1) = \frac{B}{n} \left(E_\pm^{-n} - E_o^{-n} \right) dt. \tag{7}$$

With $n \sim 10$ we see that the first part of a thick ($T \gtrsim 0.75$) radiator will contribute very little to the electron production, although it will produce pion background.

I would guess that a 0.3 radiation length radiator is probably close to the optimum, but this should clearly be worked out in more detail at the appropriate time. Along with this guess goes another: that the appropriate value to use for t in this case is not 0.3 but 0.2, to allow for some loss by straggling.

Table I has been calculated using Eq. (3) with $t = 0.2$, $A = 12.6$, $E_o = 150$. It will give an overestimate of $\times 2$, since the π^+, and not the π^0, spectrum was used. 2×10^{13} protons/pulse are assumed to interact.

Table I. Calculated Electron Yields
And Several Secondary Beam Energies.

Energy	Electron Flux* per Proton per Sterad per GeV/c	(π^+ produced) $\div$ (Electrons in Beam)	Electrons* per μ Sterad per 1% $\delta p/p$
75	3.3	5.7	5×10^7
100	0.151	84.0	3×10^6
125	0.0151	420	3.8×10^5

*See text

The steepness of this spectrum compared with the E^{-1} shape of the Bremsstrahlung from the second radiator makes it obvious that 70-GeV photon physics will be better done using the Bremsstrahlung of 75-GeV electrons rather than of 125-GeV electrons.

Very Pure Electron Beams

A method which might be considered for improving the purity of the electron beam is the reverse of the technique described by Barna et al.[5] to remove electron contamination from a pion beam. It is to place a thin radiator at the first momentum analysis slit of the beam. Electrons which have radiated an amount of energy greater than the momentum resolution of the optical system may be separated from the other charged particles at the second, dispersion-free focus. The momentum bite may be as much as a factor of 10 more than the resolution. The radiated photon spectrum is ~ tdk/k. Consider a resolution of 0.1% and let us accept in the final stages of the beam an electron-momentum bite of 10%. There will be $t \ln 100$ electrons which have radiated between 0.1% and 10% of their initial energy. For $t = 0.02$ this is about 9% of the electrons incident. (If we use $t \gtrsim 0.02$, we will have to use the correct straggling formula.)

Conclusions

The best method to produce an electron beam at NAL is the one sketched in Fig. 1. The beam-transport system might be any small angle, high-energy hadron beam focused on the EPB target. The radiator should be thin (~ 0.3 radiation lengths), and placed as close to the first element in the beam as possible, consistent with a coulomb scattering broadening of the apparent target of ~ the target diameter. The number of electrons in the beam per pion produced in the EPB target is 1/6 at 75 GeV, 1/84 at 100 GeV and 1/420 at 125 GeV. This leads to electron fluxes of a few times 10^7 at 75 GeV down to a few times 10^5 at 125 GeV. Beam purity should be very good, but has not been calculated explicitly.

REFERENCES AND FOOTNOTES

[1] C. A. Heusch, UCRL-16830, Vol. III, p. 156 et seq. (also private communication by R. Wilson).

[2] Caveat The 0^o π^+ flux in graphical form was readily at hand at the time this was written. The absolute values will be ~ × 2 too high for π^o, and the shape may not be exact. This should not affect the general conclusions.

[3] Done on a slide rule; may not be very reliable.

[4] Y. S. Tsai and V. Whitis, SLAC Pub. 184, 1966.

[5] A. Barna et al., Phys. Rev. Letters 18, 360 (1968).

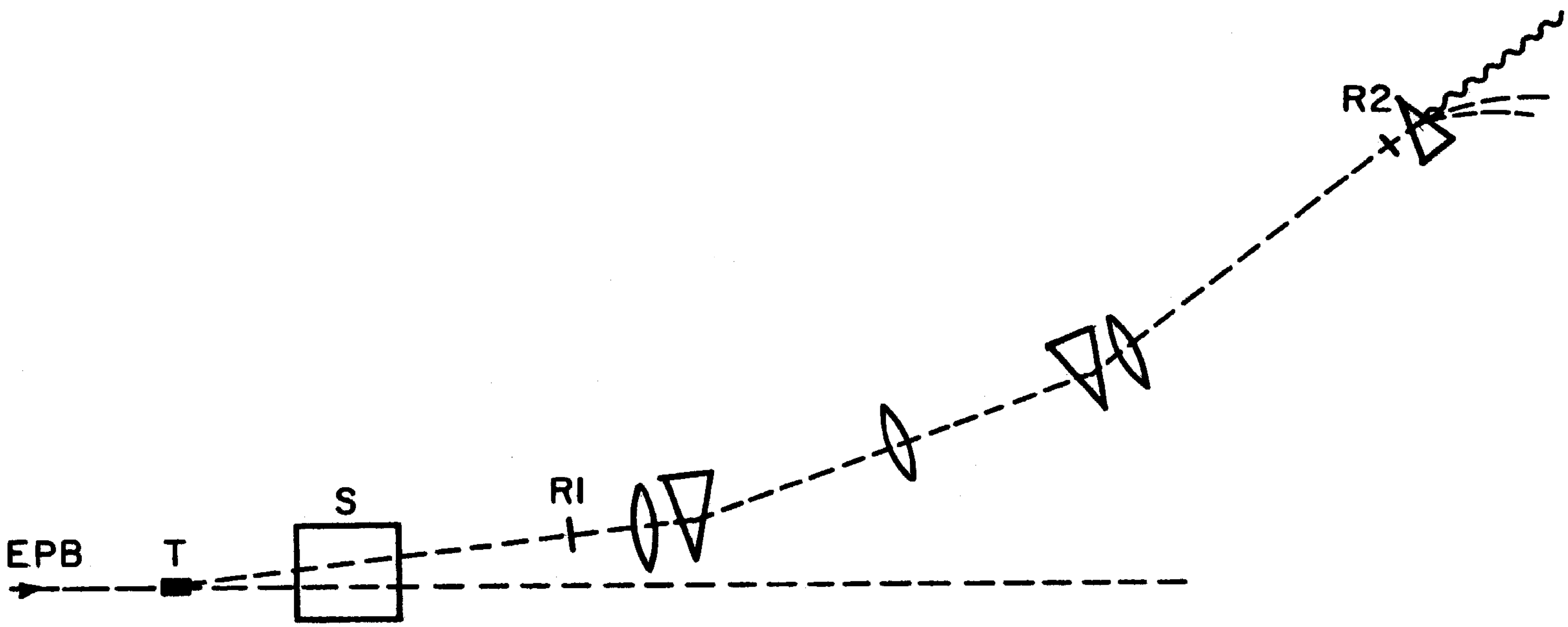

Fig. 1. Electron-photon beam: T = target, S = sweeping magnet (vertical deflection), R_1 = radiator, γ--e^+e^-, R_2 = radiator, $e^\pm$--γ.

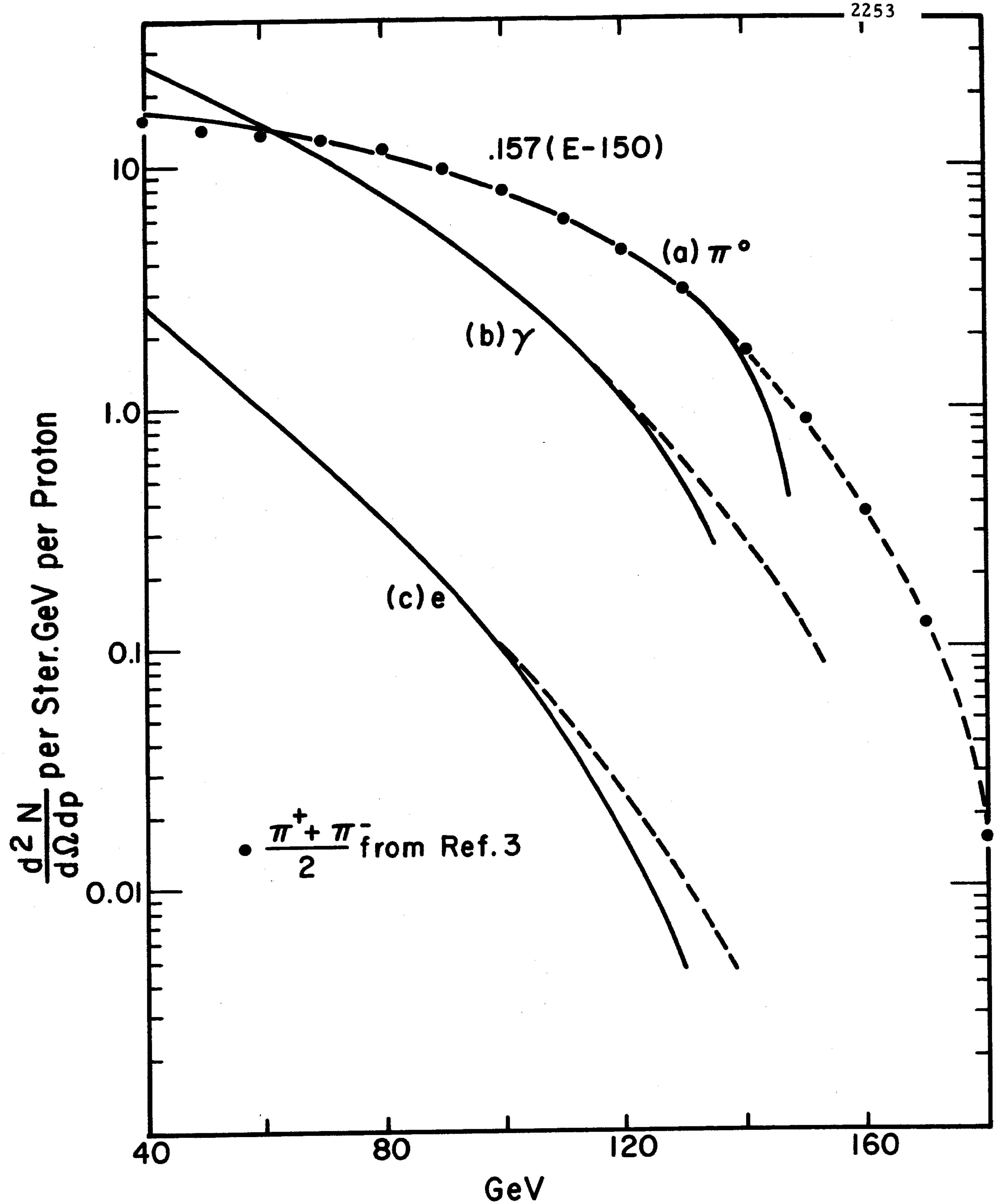

Fig. 2. Neutral pion, gamma, and electron fluxes at 0° production angle.